Systems Approach to Energy Efficient Building Operation: Case Studies and Lessons Learned in a University Campus

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ABSTRACT

This paper reviews findings from research conducted at a university campus to develop a robust systems approach to monitor and continually optimize building energy performance. The field analysis, comprising three projects, included detailed monitoring, model-based analysis of system energy performance, and implementation of optimized control strategies for both district- and building-scale systems. One project used models of the central cooling plant and campus building loads, and weather forecasts to analyze and optimize the energy performance of a district cooling system, comprising chillers, pumps and a thermal energy storage system. Full-scale implementation of policies devised with a model predictive control approach produced energy savings of about 5%, while demonstrating that the heuristic policies implemented by the operators were close to optimal during peak cooling season and loads. Research was also conducted to evaluate whole building monitoring and control methods. A second project performed in a campus building combined sub-metered end-use data, performance benchmarks, energy simulations and thermal load estimators to create a web-based energy performance visualization tool prototype. This tool provides actionable energy usage information to aid in facility operation and to enable performance improvement. In a third project, an alternative to demand controlled ventilation enabled by direct measurements of building occupancy levels was assessed. Simulations were used to show 5-15% reduction in building HVAC system energy usage when using estimates of actual occupancy levels.

Introduction

One of the problems that contribute to higher than expected energy use in commercial buildings is the lack of actionable data and analysis tools to link control strategies, operations and energy use in the built environment. Conventional building operations are subject to several problems. Monitoring and diagnostics systems rely on a variety of measured data sources to gain insights to the actual building performance, with limited understanding of the information uncertainty and lacking a simple and actionable operator interface. Such limitations result in the inability to diagnose and have corrective actions when the building or its systems are not behaving as expected. Use of fixed schedules and equipment set points (based on equipment performance optimization) limit the ability to achieve overall energy use reduction. The projects described here aimed to address such problems and assess approaches to minimize energy waste and optimize operations in commercial buildings. The following describes three closely linked projects conducted at the University of California, Merced (UC Merced) to implement and evaluate technologies at a district and building scale for enhanced facility operations and energy performance through use of improved control and visualization tools, enabled by data and system-level models. The efforts take advantage of the state-of-the-art monitoring systems deployed at the UC Merced campus. A strong commitment to energy efficient building design and operation as well as sustainability have resulted in deployment of a program to design buildings that consume half the energy and peak demand of other university buildings in California (Brown 2002) and numerous LEED new construction green building certifications (6 LEED Gold and 1 LEED Silver to date). The campus uses an energy management and control system (EMCS) through which energy and equipment performance data can be remotely accessed. This includes a comprehensive monitoring and metering system in which over 10,000 points are tracked across 900,000 ft^2 of built space (see Granderson et al. 2009).

Research and Development Goals and Objectives

- **Model predictive control of chilled water plant system.** The overall goal was to assess the feasibility and energy performance benefits of optimal control of the central cooling plant. The objective was to evaluate the feasibility of and to demonstrate the energy savings potential of model predictive control (MPC) for set-point optimization and scheduling of a district cooling system with thermal storage serving the UC Merced campus. Energy savings for the demonstration were expected to be around 10% based on published simulation and experimental studies of MPC applied to chilled water plant with storage (Flake 1998; Henze et al. 2005).
- **Energy performance visualization system.** The project objective was to demonstrate real-time energy performance visualization capability for the UC Merced Classroom and Office Building (COB). An approach which combined sensor data with building thermal and energy performance models was developed. The project aimed to demonstrate the following advances: (i) techniques to process data sources of loads and environmental variables with quality metrics for comparison with performance benchmarks; (ii) whole building energy simulations suitable for real-time use; and (iii) a prototype of a real-time performance monitoring system that integrates these elements to visualize actionable information. When implemented with the full capability, this technology will enable building data to be easily accessible by a broader community for research and provide operators with a sufficiently detailed and transparent understanding of facility operation to track energy usage against performance benchmarks and diagnose operational issues.
- **Occupancy-based energy management system.** The objective of this project was to investigate opportunities to reduce energy use in a UC Merced building by adjusting the HVAC system operation, based on real-time knowledge of actual building occupancy and contrast with traditional CO_2 sensor-based demand controlled ventilation strategies. The research focused on the Science and Engineering (SE) building and COB and included analyses to: (1) determine the building control options and associated energy benefits for a given level of detail about occupancy (e.g., spatial distribution and temporal resolution), and (2) characterize the sensor hardware and assess models needed to directly estimate building occupancy.

Technical Approach and Methodologies

Model Predictive Control

MPC offers energy saving potential in large buildings and systems for which response to external disturbances or control inputs is slow, i.e. on the order of hours. MPC effectively provides a means to optimize systems dynamically to take advantage of building utilization, weather patterns, and utility rate structures. An MPC scheme was developed and tested for the UC Merced campus chilled water system. The control algorithms were implemented in MATLAB, with readily available tool boxes for rapid development and performance assessment. Dynamic models of the chilled water piping system and of the buildings were developed in the Modelica language (Wetter 2009) and used as the basis of the MATLAB models and lookup tables for use in the control policy design.

The main components of the campus chilled water system are schematically depicted in Figure 1. The chilled water plant consists of three 1,200 ton chillers, a cooling tower, a 2,000,000 gallon thermal energy storage (TES) tank, a primary chilled water distribution system and secondary distribution loops serving each building, managed by a single building automation system. The existing controls maintain 39°F leaving water temperature and the chillers are sequenced manually to maintain each chiller as close to full load as possible while producing sufficient stored chilled water for the following day.

Detailed descriptions of the individual components comprising the chilled water plant are presented in Haves et al. (2010) and in Ma et al. (2009, 2010). Two TES tank models were developed to predict the total stored cooling capacity, the temperature of the water supplied to the campus, and the temperature of the water returned to the chiller. In the more detailed model, the temperature profile in the tank is modeled by discretizing the tank into a number of layers. For online optimization, a low-order model was developed in which the cool and warm water are treated as lumped masses and the thermocline between the warm and cool water is treated as a moving boundary, thus requiring only three dynamic states, i.e. the position of the thermocline and the temperature of each lumped mass. The control design includes a simple, lumped parameter model that predicts the total campus cooling load based on the ambient temperature, the cloud cover, the time of day and the day of the year.

The aggregate campus chilled water flow rate and return temperature are predicted by a single cooling coil model that represents the combined effect of all the cooling coils on the campus. The model parameters are identified from measured data. Figure 2 shows a comparison of the predicted and measured cooling load and return water temperature. Based on building load and weather forecasts, optimal control policies were created to adjust chilled water plant set-points including leaving water temperature, cooling tower return temperature, chiller staging, and the volume of chilled water stored in the tank. A cost function that includes energy consumption and peak electrical demand over a 24-72 hour prediction horizon was formulated and solved using a one hour time-step (Haves et al. 2010, Ma et al. 2009, 2010).

Figure 1: Schematic Diagram of UC Merced Chilled Water System

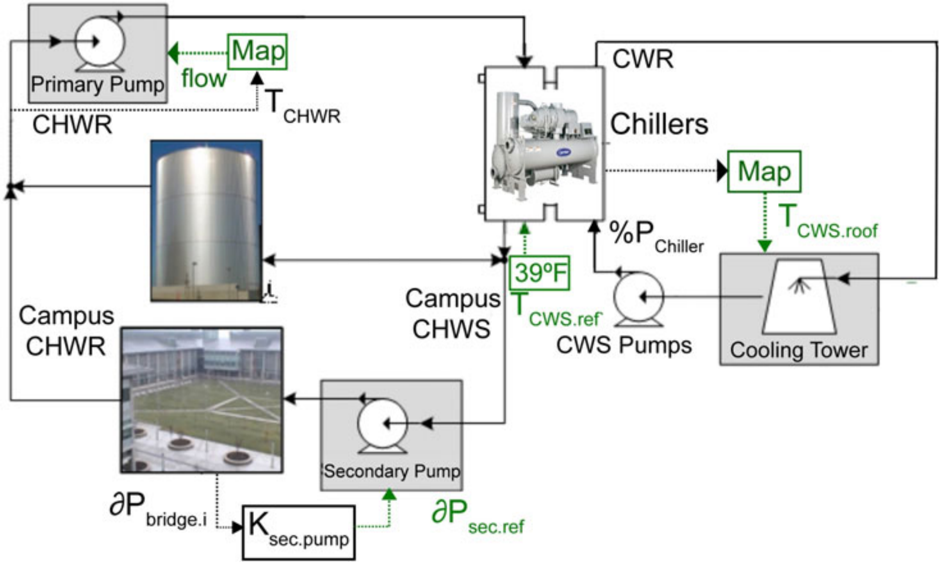
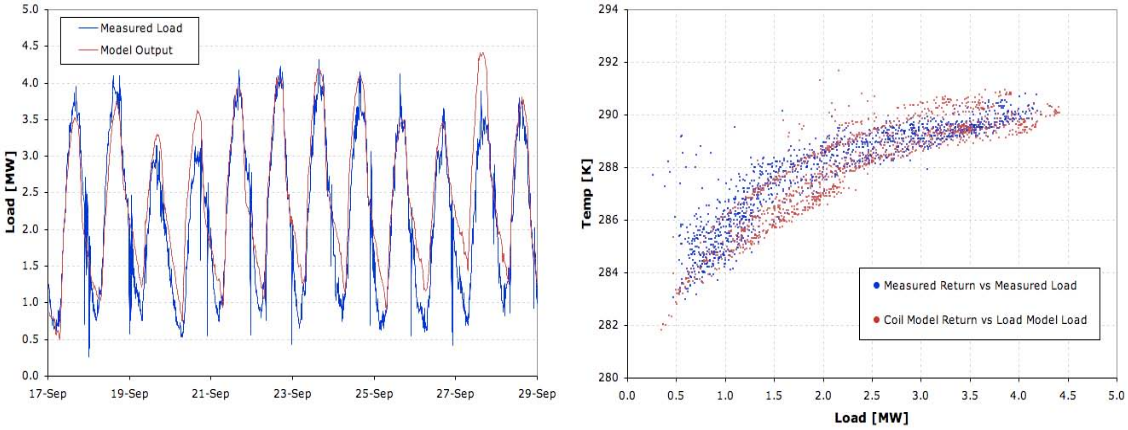


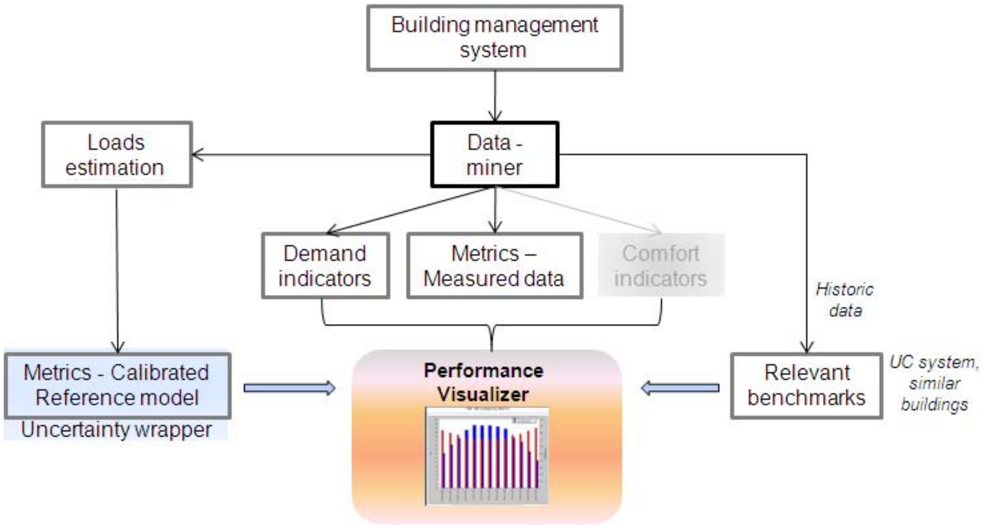
Figure 2: Fall 2009 (a) Campus Cooling Load, (b) Campus Return Temperature versus Load



Energy Performance Visualization System

The visualization system aimed to provide concise information on building system conditions, utilization, operation, and energy performance broken down by end use. A prototype was developed and evaluated for the COB at UC Merced. The main components of the visualization prototype are depicted in Figure 3.

Figure 3: Performance Visualization Tool Framework and Key Elements



Building Management System Database

Data is recorded by the building management system (BMS) for control, stored locally for a short period of time, and is then archived to a database. The trending data is transferred to a dedicated server that is queried from the visualization tool.

Data Miner

The data miner was developed with a web-based GUI that processes the archived data for use by the visualization tool and to make it easy for users to access and manipulate both the archived data and the outputs of the building model (described later). The website serves as the interface through which users query the SQL database. Through this site users have the ability to plot and download datasets of their choosing, i.e. the specific operational variables and energy use information and required time intervals (daily, monthly or annual). The ability to modify basic plotting features, such as the choice of daily averages and edge plots, allows for customized visualization of the data. Importantly, as the pre-processing tool for trend data, the data miner serves as an inspection point for data quality.

Performance Metrics

Performance metrics consolidate the vast amount of energy data, usually trended as part of the BMS, into standardized quantities for easier and quicker understanding of the building operation. Performance metrics based on prior work (e.g., Gillespie et. al. 2007), for three categories were developed – whole-building (e.g., total energy consumption, cost, carbon emissions), end-use energy, and operational efficiency (e.g. cooling plant, heating, fan efficiencies). The metrics were calculated from the UC Merced metered trending data, and were tailored based on the campus facility manager’s feedback. Table 1 outlines the data needed for each of the metrics at the whole building level and the procedure for calculating the metric (for details see Apte et al. 2010). The performance metric value depends on the demand indicators including heating and cooling degree-days and percent of hours the HVAC system is in the occupied mode. Comfort indicators to be implemented will include the space heating and cooling set points. There are usually several periods when the data is either not logged or logged incorrectly. Decisions on whether data is incorrect are made based on domain expertise using standard imputation techniques. For all metrics, the percent of missing values is reported, giving the user a confidence rating, and providing transparency that is lacking in typical EMCS.

Table 1: Data Requirement and Calculation Procedures for Building Performance Metrics[1]

Metric	Unit	Data	Calculation[2]
Total electricity consumption	kWh/yr/gsf	• kW data at every time step, for a whole year • Total gross sq.ft. (incl. the wall)	Sum (kW data at every time step)
Electricity demand	kW/gsf	Same as above	Max (kW data at every time step)
Total gas consumption	therms/gsf-yr	• Therms/hr hot water data at every time step, for a whole year • Total gross sq.ft. (incl. the wall) • Central boiler plant efficiency	Sum (therms/hr gas consumption data at every time step)
Gas demand	therms/hr-gsf-yr	Same as above	Max (therms/hr gas consumption at every time step)

The points to trend in a BMS are typically decided based on operational requirements, and not from energy performance standpoint. For the COB, the trended dataset is rich and maps almost one-to-one to the performance metrics outlined here. The one case where it does not map directly is for interior lighting power consumption because other electric circuits (e.g. outdoor lighting, certain pumps) are mixed into the lighting power metering panel.

Performance Benchmarks

Historic baseline data and whole-building reference models allow for comparison of current performance with benchmarks at system, sub-system, component (e.g., fan coil), and component parameter level (e.g., fan coil temperature, water flows). For this project, benchmarks for annual consumption based on comparable buildings (Brown 2002) are used (see Table 2). For some metrics, design intent/standards are used as benchmarks. Benchmarks can also be derived from whole-building and end-use stock models such as LBNL's EnergyIQ (http://energyiq.lbl.gov/SupportPages/EIQ-about.html), drawing upon analysis of the California End Use Survey (Mathew et al. 2008). For COB, historic data are available to generate same building historic baseline data for every metric and at any time interval. The comparable building benchmarks are based on 1999 UC/CSU campus benchmarks (Brown 2002), and are calculated using regression models, accounting for space usage (e.g., percent office or laboratory space) and climate. Another set of benchmarks are goals used in energy efficient designs. For example, 1 cfm/ft^2 is a typical metric for installed fan flows. This number tends to be lower (~ 0.8 cfm/sq.ft.) for more efficient designs. A careful presentation of COB benchmarks, targets, and actual performance can also be found in a New Buildings Institute study[3].

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[1] See Apte et al. 2010 for more details on measurements and on end use energy metrics

[2] Calculated quantities have the product of (the number of time steps in one hour) x (building gsf) in the denominator.

[3] http://www.newbuildings.org/sites/default/files/Case_Study_UCM-COB.pdf

Table 2: Comparable Building Benchmarks Used for COB

	Units	Target	Comment
Max Electric Demand	W/gsf	3.65	Includes allocated cooling plant, building exterior lights, and allocated campus road lights
Annual Electric Use	kWh/yr/gsf	15.1	
Max Gas Demand	Th/hr/kgsf	0.12	Includes hot water and heating
Annual Gas Use	Th/yr/gsf	0.2	
Max Cooling	Tons/kgfs	2.03	

EnergyPlus Simulation Model

With the advent of the LEED rating system the use of whole building energy simulations for design is becoming common. These models (appropriately calibrated) can be used during operation, to track expected performance, and to understand sub-system behavior to isolate operational problems and identify means to improve building energy performance. A simulation model for the COB was created using EnergyPlus version 4.0.0.024 (see Figure 4). Details of the model are provided in Apte et al. (2010), and its calibration is still in progress. Models for the building surfaces (i.e. walls, insulation, overhangs and glazing) were incorporated. Key internal loads modeled were people, lights, and plug-load equipment and were specified for each model zone by a maximum value (people and lights) or a per floor area value (equipment). Occupancy level and lighting power information was obtained from architectural drawings. Weather files for the years 2008 and 2009 were compiled from several sources (UC Merced: air temperature and wind speed; direct normal radiation: California Department of Water, San Luis Reservoir site; relative humidity for 2008 Fresno International and Merced Municipal Airports). Electrical consumption by lighting, equipment, and fans was disaggregated into categories corresponding to the electric sub-meters installed in the COB. Figure 5 shows preliminary comparisons of simulation results and sub-metered data, showing discrepancies from factors such as improperly matched schedules (Apte et al. 2010).

Indoor thermal load estimation. Insights into the dynamics of building loads can help understand and optimize building energy performance. When available, sensors within the terminal units and indoor environment can provide useful information, but they can be grossly inaccurate when estimating loads over extended periods of time because of accumulating errors. An approach to estimate internal loads combining simple thermal network models (3R2C) with real-time data from the BMS was implemented. The estimated internal loads were compared to measured data from the COB to ensure consistency (O'Neill et al. 2010). The internal load was estimated in a lumped form including internal lighting, equipment, people, infiltration and inter-zone mixing. The estimation captures the daily (daytime vs. nighttime) and weekly (weekday vs. weekend) variation for the loads and can shed light on anomalies in energy performance or operations.

Figure 4: Model Representation of COB Showing Glazing and Overhangs.

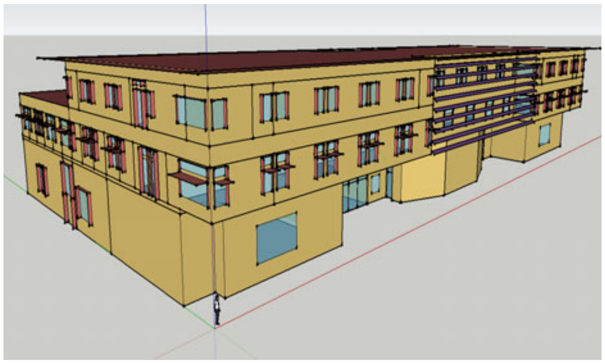
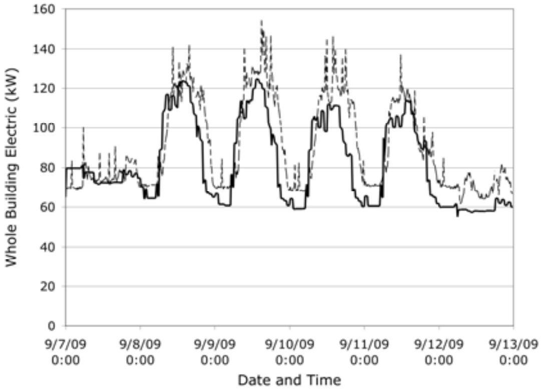


Figure 5: EnergyPlus Predictions (solid) Compared to Measured (dashed) Building Electric Consumption for Sep. 2009.



Performance Visualizer

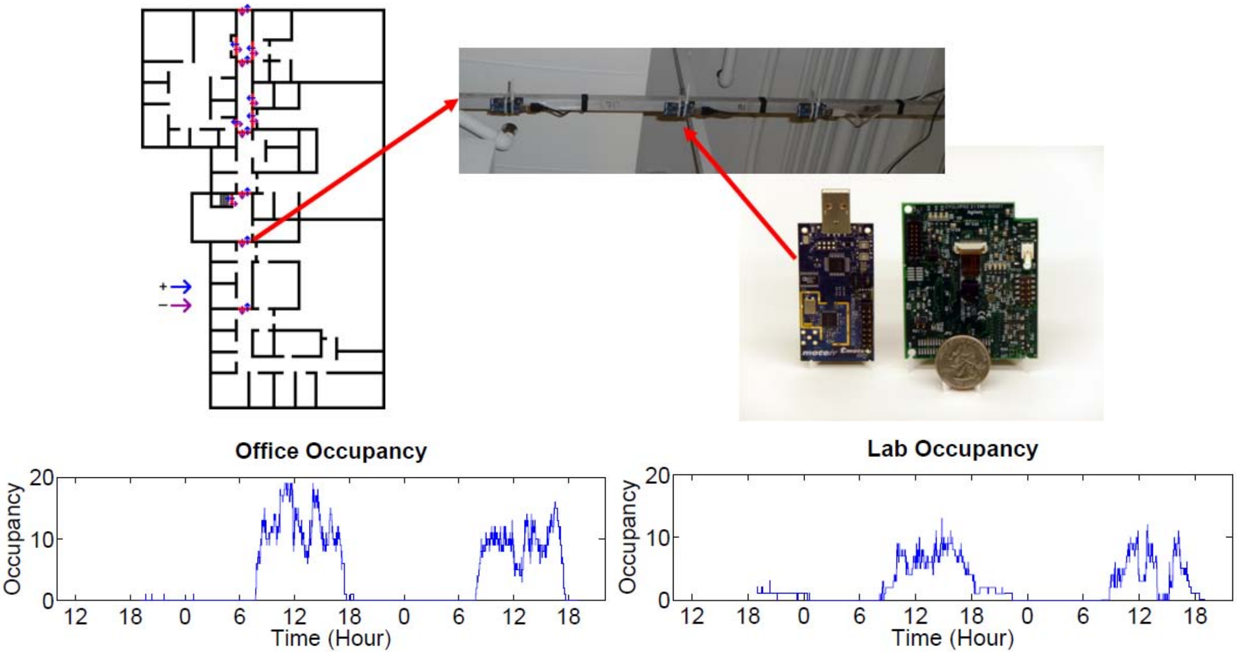
The performance visualizer provides an integrated environment and interface to display the metric values for the measured data and their historic values, the benchmarks, zonal loads where appropriate, and the reference EnergyPlus model side by side. The metrics can be visualized at yearly, monthly, weekly as well as daily intervals. In addition, for a given metric, the individual data points and demand indicators can also be displayed.

Occupancy-Based Energy Management System

The experiments to determine the feasibility of directly measuring or estimating the number and location of occupants in a building using a wireless network of low-power, low-resolution cameras were conducted in the SE building. The energy-savings potential from knowing the distribution of occupants was evaluated for the COB. An existing eQUEST model of COB, developed during building design (Taylor engineering 2002), was analyzed to evaluate the energy savings potential of using direct occupancy estimation for ventilation control. The details of deploying a network of wireless camera sensors in the SE building are discussed in Erickson et al. 2009. When an occupant crosses key transition points (see Figure 6), the cameras capture and process the images to determine actual occupancy count. The resulting traces (see Figure 6) were used to train occupancy models (see Erickson et al., 2009). A combination of prior knowledge on building usage and models of traffic patterns in SE building faculty and graduate student offices and public areas were used to generate occupancy patterns for the COB in similar areas (where occupancy sensors were not available). Available schedules for different days were used for classrooms, simulating the use of error-free CO_2 sensors in the COB. The approach was as follows: (i) generate occupancy schedules for use in simulation environment; (ii) adjust control setpoints (temperature and ventilation levels in individual zones) based on occupancy level; (iii) use eQUEST model to predict energy consumption with control strategies. For design, occupancy was described by one class schedule and one office schedule for all seasons and classroom and office zones, respectively. To estimate the savings due to control based on direct measurement of occupancy, schedules are updated – each classroom has a unique schedule. The classroom schedule varies, based on the day of the week, season, and vacation.

Each office zone has a unique schedule, generated from the occupancy movement model (Erickson et al. 2009). The occupied time is assumed to be from 7AM to 9PM. The minimum flow ensured in spaces is 40% in classrooms, auditoriums, and conference rooms and 30% in offices. Literature-based estimates on demand controlled ventilation (employing CO_2 sensors in every zone) suggested the potential for reducing HVAC energy consumption by 10-20% in a typical office building (Emmerich and Persily 2001).

Figure 6: Wireless Camera Sensor Network Deployed in Second Floor of SE Building (top), Typically Observed Occupancy Patterns in Lab and Office Spaces in SE Building (bottom)

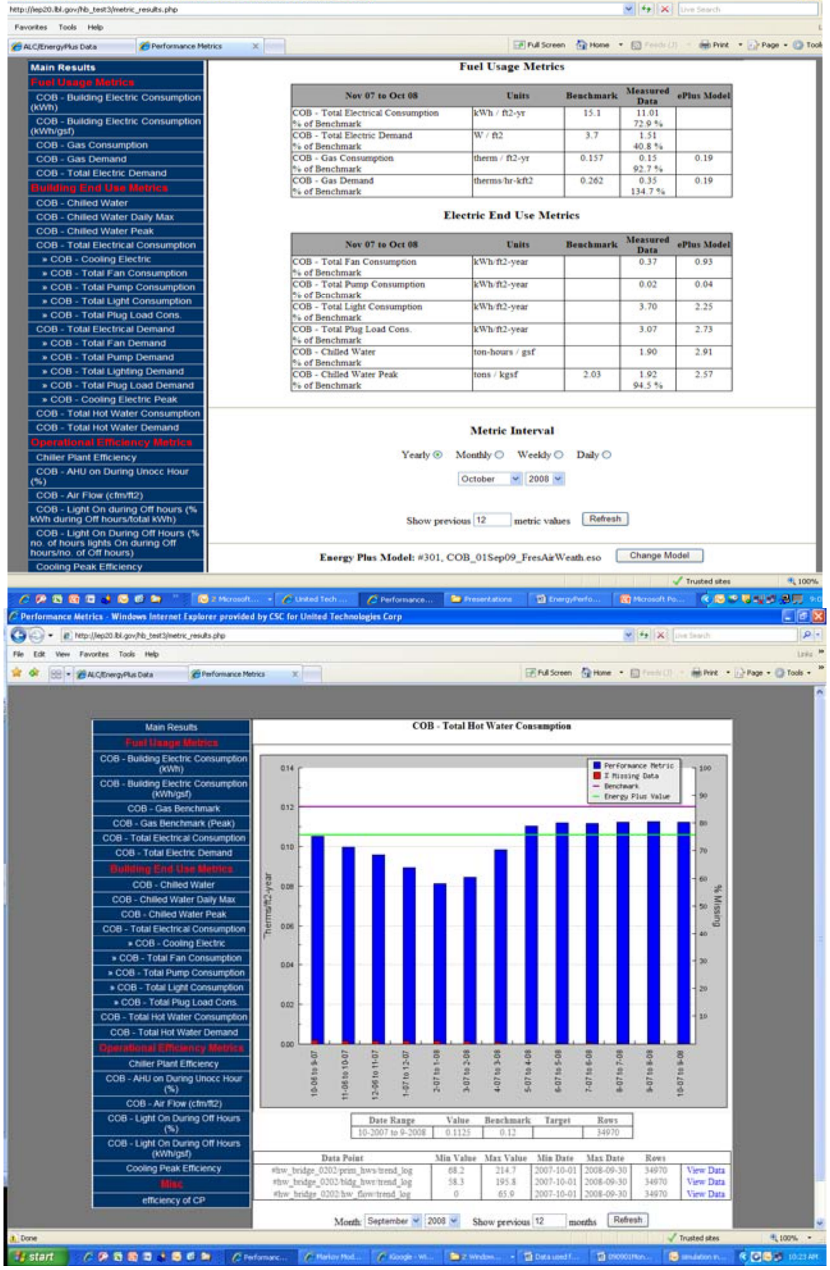


Summary of Results

- **MPC for chilled water plant.** Opportunities to optimize the chilled water plant runtimes were identified to take advantage of ambient conditions and eliminate overcharging of the chilled water tank. Two MPC experiments were carried out with the central cooling plant. The first was a week-long test in June 2009 during the summer/peak cooling season. Various algorithm and modeling bugs were found during this test, and performance improvements from the MPC implementation were not evident (Haves et al. 2010). Suboptimal choice of charging window length for the algorithm affected the overall COP adversely. However, an increase in system COP by increasing the standard condenser water set-point (CWS) range from 57-60^{o}F to 65-66^{o}F was learned as a useful policy modification. Regression analysis suggests the COP improvement potential for the CWS change is approximately 1.5%, although this was difficult to confirm due to the multiple changes that occurred simultaneously. A second MPC experiment was conducted in October 2009; the cooling load was much lower than during the summer. The incremental energy savings relative to the original manually implemented policy were 4.6%±2.4%. A simplified tool with rules derived from the above experiments is now being implemented at the UC Merced central plant. The campus load and plant models developed have also proved to be a useful commissioning tool for facility operation. For instance, it was determined that the CHWS set-point and the chilled water flow rate can be used to limit the chiller loading to prevent chiller surging. Inconsistencies in central and buildings-level return temperature data for campus load modeling led to the identification of a malfunctioning flow rate sensor in one of the buildings, which caused higher demands for chilled water and reduced chilled water return temperatures. The testing process also led to identification of simple modifications to the heuristic control policy currently used by the operators. It was found that operating the chillers near full load was a key factor in maximizing system efficiency, leading to the recommendation to operate a single chiller (at near peak load) in off-peak regimes (e.g. transition/shoulder seasons).

- **Energy performance visualization for COB.** The performance visualizer displays metrics for measured data (including historic values), benchmarks, and a reference model side by side. For a given metric, the individual data points and demand indicators can also be visualized. Screenshots from the prototype are shown in Figure 7. The prototype supports performance tracking, and to some extent, the localization of performance degradation and faults to a sub-system/parameter level. This is enabled by time-series charts for the metrics that compare measured performance with benchmarks, historical same-building data, and metrics from a calibrated, reference whole building EnergyPlus model. The visualizer enables correlation between variances in energy performance measurements or dynamic indoor load estimates and relevant equipment operational variables. In one instance, a problem with secondary pump control for COB hot water delivery that was responsible for a temporary 36% increase in whole building heating energy use was identified and repaired.
- **The occupancy-based energy management system.** Energy savings analysis from the use of occupancy-based controls was conducted for the COB. Three ventilation control strategies were simulated. In the base case, the outside air (OA) quantity is set based on maximum design occupancy. This quantity is fixed during occupied times, irrespective of the occupancy level, and commonly implemented. The COB eQUEST model was used to establish baseline energy consumption. A 4-5% reduction of the annual whole building energy consumption was estimated compared to the base control strategy and only a marginal improvement of ~1% from the current control strategy was observed (which utilizes CO_2 sensor-based demand controlled ventilation for two-third's of the space); applicable ventilation code requirements (ASHRAE 62.1 2007 and Title 24) were ensured. This translates to an HVAC annual energy consumption reduction of about 14% using actual occupancy estimates and a 4% energy use reduction when compared to current control strategy (Table 3). Note that the current demand controlled ventilation strategy simulated is assumed to be free of sensor uncertainties, which can be up to 20% for CO_2 sensors.

Figure 7: Comparison of Benchmark, Measured Data, and Reference Model for Whole Building Fuel Usage and End-Use Performance Metrics



Fuel Usage Metrics

Nov 07 to Oct 08	Units	Benchmark	Measured Data	ePlus Model
COB - Total Electrical Consumption % of Benchmark	kWh / ft2-yr	15.1	11.01 72.9 %	
COB - Total Electric Demand % of Benchmark	W / ft2	3.7	1.51 40.8 %	
COB - Gas Consumption % of Benchmark	therm / ft2-yr	0.157	0.15 92.7 %	0.19
COB - Gas Demand % of Benchmark	therms/hr-kft2	0.262	0.35 134.7 %	0.19

Electric End Use Metrics

Nov 07 to Oct 08	Units	Benchmark	Measured Data	ePlus Model
COB - Total Fan Consumption % of Benchmark	kWh/ft2-year		0.37	0.93
COB - Total Pump Consumption % of Benchmark	kWh/ft2-year		0.02	0.04
COB - Total Light Consumption % of Benchmark	kWh/ft2-year		3.70	2.25
COB - Total Plug Load Cons. % of Benchmark	kWh/ft2-year		3.07	2.73
COB - Chilled Water % of Benchmark	ton-hours / gsf		1.90	2.91
COB - Chilled Water Peak % of Benchmark	tons / kgsf	2.03	1.92 94.5 %	2.57

Metric Interval

Yearly ● Monthly ○ Weekly ○ Daily ○

October 2008

Show previous 12 metric values

Energy Plus Model: #301, COB_01Sep09_FresAirWeath.eso

COB - Total Hot Water Consumption

Date Range	Value	Benchmark	Target	Rows
10-2007 to 9-2008	0.1125	0.12		34970

Data Point	Min Value	Max Value	Min Date	Max Date	Rows	
#hw_bridge_0202/prim_hws/trend_log	68.2	214.7	2007-10-01	2008-09-30	34970	View Data
#hw_bridge_0202/bldg_hws/trend_log	58.3	195.8	2007-10-01	2008-09-30	34970	View Data
#hw_bridge_0202/hw_flow/trend_log	0	65.9	2007-10-01	2008-09-30	34970	View Data

Month: September 2008 Show previous 12 months

Table 3: Saving Calculations Based on ASHRAE 62.1 2007 Ventilation Requirements

Values in MMBtu	Heating	Cooling	Heat Reject	Pumps	Fan	HVAC	% Savings HVAC	Total	% Savings Total
Base Control Strategy	335	252	5	150	128	870	-	2578	-
Current Control Strategy	327	214	4	141	101	786	10%	2494	3.3%
New Control Strategy	293	212	4	140	101	750	14%	2457	4.7%

Concluding Remarks

The UC Merced research projects explored new methods to combine measurements, simulation models, control strategies, and information feedback to improve facility operation and reduce energy consumption in buildings. The cooling plant optimization project showed that dynamic system models could be used to identify critical control variables (from an energy performance standpoint), guide facility operation, and produce a predictive controller that reduces energy use. Full-scale implementation of control policies based on model predictive control demonstrated that the heuristic policies implemented by the operators were quite close to optimal; policies based on model predictive control produced energy savings of 5%. The methodology is extensible to air-side HVAC systems and to building hydronic systems where variable speed technologies are becoming prevalent and robust, multivariable control methods are lacking. The projects extended the use of data into new analysis platforms for direct use by facility operators. The flexible and transparent web-based visualization prototype illustrates that comparative performance metrics are an effective way to understand the energy and operational performance of the building compared to current methods of data trending. With the visualization prototype providing comparison of performance metrics to previous years, building models, and benchmarks, the facility manager can assess the energy and cost savings of a particular action with relative certainty; a traditional BMS may not store data for the length of time necessary to provide such insight, nor does it provide relevant benchmarks or models to show how the building is expected to perform. The prototype comprising measured data and benchmarks is now being updated with new metrics and implemented operationally at UC Merced. It is anticipated that the value of this tool will become more apparent as various building systems age and require commissioning. It has been recognized that building energy consumption and electricity demand can be reduced by 10-15% when actionable energy usage information is provided to facility managers and operators (Mills and Mathew 2009) and the visualization prototype developed here is the first step in enabling this. Preliminary results from the occupancy-based energy management study revealed incremental benefits over conventional demand controlled ventilation strategies, indicating energy-savings potential arising from setting outside air ventilation based on measurements of the actual number of building occupants. Savings are anticipated to be higher in buildings where an extensive CO_2 sensor network (such as in the COB) may not be available.

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